Inherent Deformation Problems of State-of-The-Art Commercial Practice

Despite significant efforts and the ever increasing need for light weight magnesium wrought products, limited commercial application of forming processes for magnesium alloys has been realized. This can be attributed to: (1) limited operative slip systems at room temperature in the hcp crystal structure [Hart1968, Ree1960, Kel1968, Bart1980, Kim2003, Bar(2007a, 2007b, 2004), Koi(2005a,2005b), Agn(2001,2003,2004,2005, 2006), Jai(2007,2008)], where for Mg the CRSS for basal slip has been shown to be significantly less than for prismatic or pyramidal slip, as reviewed by Koike [Koi2003b]; (2) the tendency to form strong textures during deformation as described in recent years by Agnew and others [Agn(2001,2003,2004,2005,2006), Jai(2007,2008), Kim2003]; (3) the highly anisotropic deformation behavior of textured microstructures that lead to macroscopically anisotropic mechanical properties [Kel1968, Agn2006, Kle2004, Koi2005a]; and (4) the prevalence of significant twinning during deformation that can lead to premature fracture, as described by Barnett [Bar2007a, 2007b,2007c), Jai(2007,2008)]. For these reasons, metal forming, which involves complex deformation paths to produce a component, is virtually impossible for ordinary grain size Mg alloys at ambient temperatures and at strain rates that are commercially viable. Microscopically, it has been shown that twinning becomes more prevalent as grain size increases, temperature decreases and strain rate increases [Yan2006, Jai2008) Mey2001] and it can cause fracture at low strains. An example of this is illustrated from the work of Barnett [Bar2007c]. Figure 1 shows crack formation associated with $\{10\bar{1}1\}$ double twins in room temperature deformation of rolled and annealed sheet derived from DC (direct cast) billet. Double twins are more favorably oriented for slip of <a> type dislocations than the parent grains from which they form, and large strains in the twins can lead to incompatibility stress and fracture [Hart1968, Ree1960, Bar2004, Yoo1981, Jai2008]. It has also been shown that activation of <c + a> slip rather than <a> slip on non basal planes is responsible in limiting ductility. Obara [Oba1973] has reasoned that this is because the <c + a> dislocations quickly dissociate into glissile <a> and sessile <c> segments greatly increasing work hardening and leading rapidly to fracture.

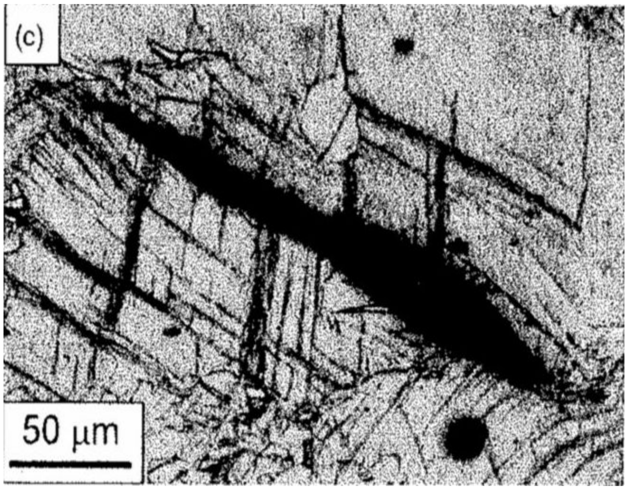


Figure 1. Crack initiation and voids in coarse grained commercial AZ31 sheet (Bar 2007c).

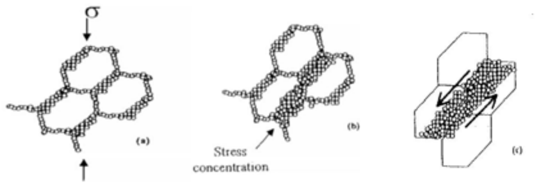


Figure 2. Twin induced heterogeneous recrystallization leading to shear banding and hot cracking in coarse-grained commercial Mg alloys (Ion1982).

Attempts to produce finer-grained stock from commercially cast alloys as a means to avoid twin-induced fracture are fundamentally limited by the microstructure and deformation behavior described above. In particular, warm deformation of coarse grained material can, through both basal slip and twinning, cause local dynamic recrystallization to form fine grains favorably oriented for deformation while at the same time leaving large grains between these soft regions where shear bands form and cause catastrophic cracking [Ion1982, del(2003, 2005b, 2008)], as illustrated from Ion's work in Figure 2. To avoid this inherent propensity, many small reductions and reheats are required to gradually coax the original coarse-grained cast material down to sheet. These small increments of reduction of large grained stock limit the ability to refine grain size and to refine eutectic intermetallic size. Such wrought commercial stock retains a grain size of 15 to 90 μm, strong texture and brittle behavior well above ambient temperature. Hence formability and mechanical properties suffer.

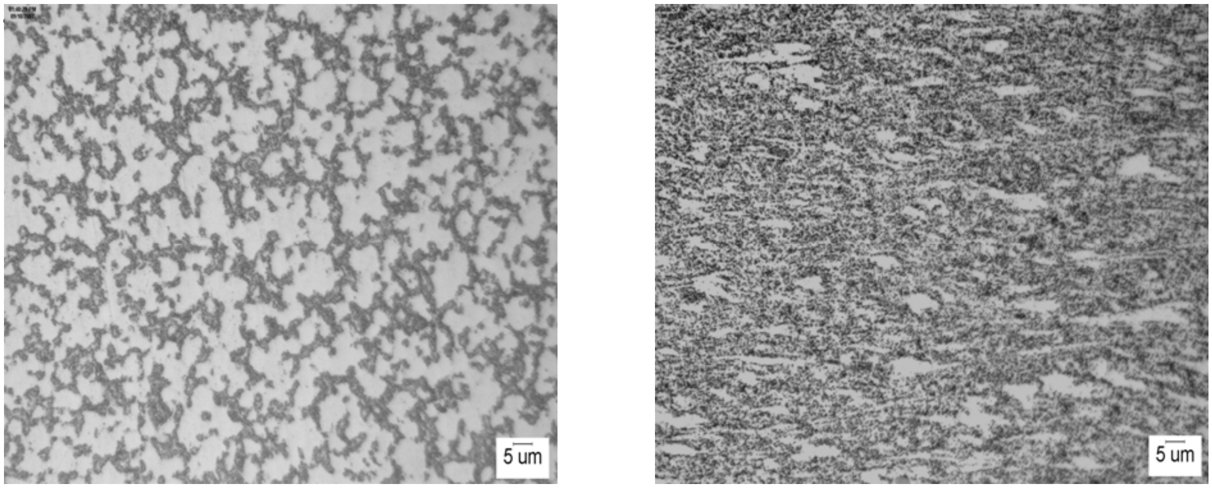
TTMP Advantage – The Microstructural and Processing Remedy for Mg Alloys

Molding fine grains ab initio is the remedy. The fast freezing rate of Thixomolding generates dendrite arm spacings (DAS) and grain sizes of about 5 μm. Twinning is minimized at this and finer grain sizes (ref, NSF STTR Phase I Project 0637203 Final Report); rather, multiple slip systems and grain boundary sliding are favored. Vigorous thermomechanical processing can be imposed in 1 or 2 passes to both subdivide the intermetallics and to further refine the grain size to micron size by continuous dynamic recrystallization. As shown by Emley(12), ductile/brittle temperature is lowered dramatically by grain refinement. Anisotropy of tensile/compression strength is minimized. Strength is boosted as grain size is reduced - by the well established Hall-Petch relationship (which effect is stronger in Mg alloys than in other structural metals). The subdivided intermetallics can then be utilized as nano-sized dispersion hardening phases rather than embrittling phases.

This is the mechanistic basis of the TTMP advance.

NanoMag Mg. Under NSF STTR Phase I Project 0637203 and Phase II Project 0847198, a new process has been invented for low cost production of fine-grained Mg alloy sheet – overcoming the decades-long barriers in state-of-the-art large grained commercial sheet. The key to this new process, Thixomolding thermomechanical processing (TTMP), is the fine grain (5-10μm), isotropic, homogeneous microstructure that is inherent in rapidly solidified Thixomolded sheet bar. The TMP step is simple and quick, consisting of "hot plate" heating and rolling in heated flat rolls. Thereby, grain size was refined by continuous dynamic recrystallization to 0.8-2 μm. At the same time, coarse intermetallic phases were refined in-situ to nanometer dispersions (see **Figure 3**). Detrimental twinning and shear banding were minimized and slip mechanisms were favored.

It was established that TTMP offers a significant cost reduction and grain size reduction compared to commercial Direct Cast (DC) and rolled Mg sheet. Furthermore, TTMP offers greatly reduced grain size, reduced edge cracking, enhanced homogeneity and improved mechanical properties compared to developmental Twin Roll Cast (TRC) and rolled sheet. For example, yield strength/density of NanoMag Mg alloy is 90% higher than commercial AZ31 sheet (see **Table I**). In the annealed condition, cold bendability of TTMP sheet was also superior to TRC sheet. It was also shown that TTMP offers a faster, more agile and lower cost route to nanostructured Mg alloys than the experimental powder metallurgy and equal channel angular extrusion (ECAP) processes. Safety problems in handling nanosize particles are obviated since such phases are generated in situ in the bulk.



a. As Thixomolded b. TMP processed in 1 step

Figure 3: Refinement of grain size and Intermetallic eutectic by TTMP

Table I. Effect of Processing on TTMP AM60

Processing	YS, MPa	UTS, MPa	Elong, %
AsThixomolded	134	240	10
As TTMP	316	368	9
TTMP+Thermal Treatment A	328	371	10
TTMP+Thermal Treatment B	244	312	21

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